Performance Evaluation of GNSS Based Railway Positioning

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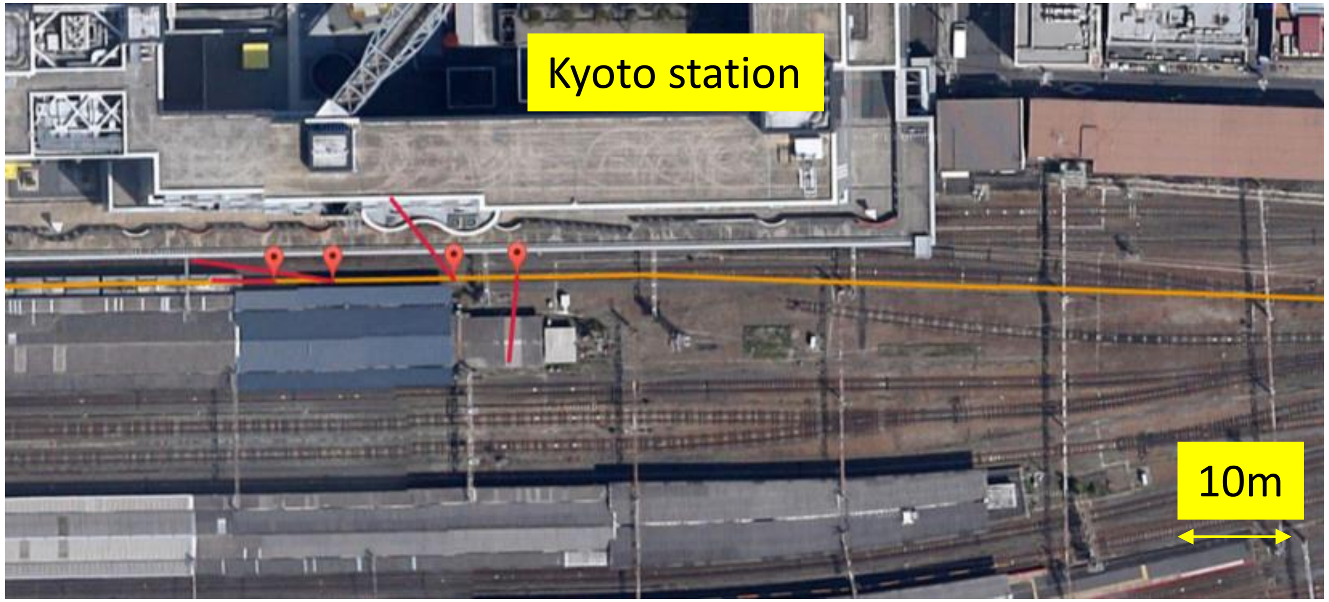
Motoki Higuchi, Nobuaki Kubo and Tomoji Takasu
(Tokyo University of Marine Science and Technology)

Haruo Yamamoto
(Railway Technical Research Institute)

Outline

- Background and Motivation
- Data Acquisition
- Multipath Error Analysis
- Multipath Error Mitigation and Results
- Conclusion

Motivation 1

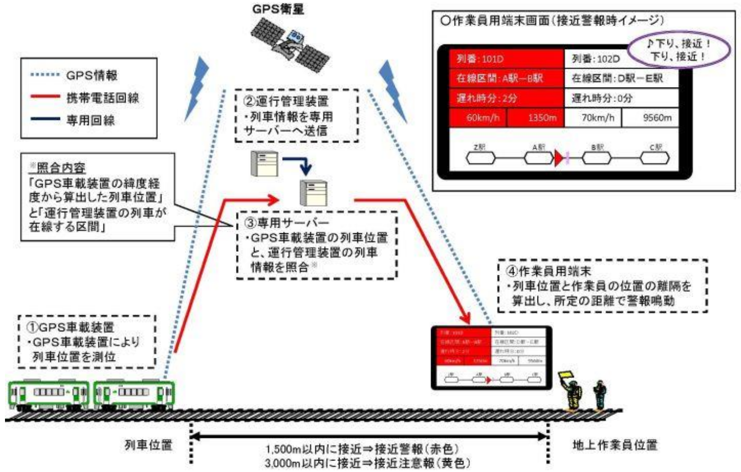


Google map

- What are the reasons of these errors ? (Multipath ?)
- How big of these errors ?
- The large errors are likely to occur at same places like shown in these pictures.
- We need to know the actual performance using long time data.
- If possible, we want to reduce these errors.

Motivation 2

- East Japan Railway Company plans to install the GNSS based warning device (lines in red) for train approach **to protect the worker** in the field.
- Red(warning) : 1500m   Yellow(caution) : 3000m
- Safety related applications requires **integrity and reliability**.
- For this purpose, **performance analysis in the real railway environment** is quite important.



※照合内容
「GPS車載装置の緯度経度から算出した列車位置」と「運行管理装置の列車が在線する区間」

①GPS車載装置
・GPS車載装置により列車位置を測位

②運行管理装置
・列車情報を専用サーバーへ送信

③専用サーバー
・GPS車載装置の列車位置と、運行管理装置の列車情報を照合※

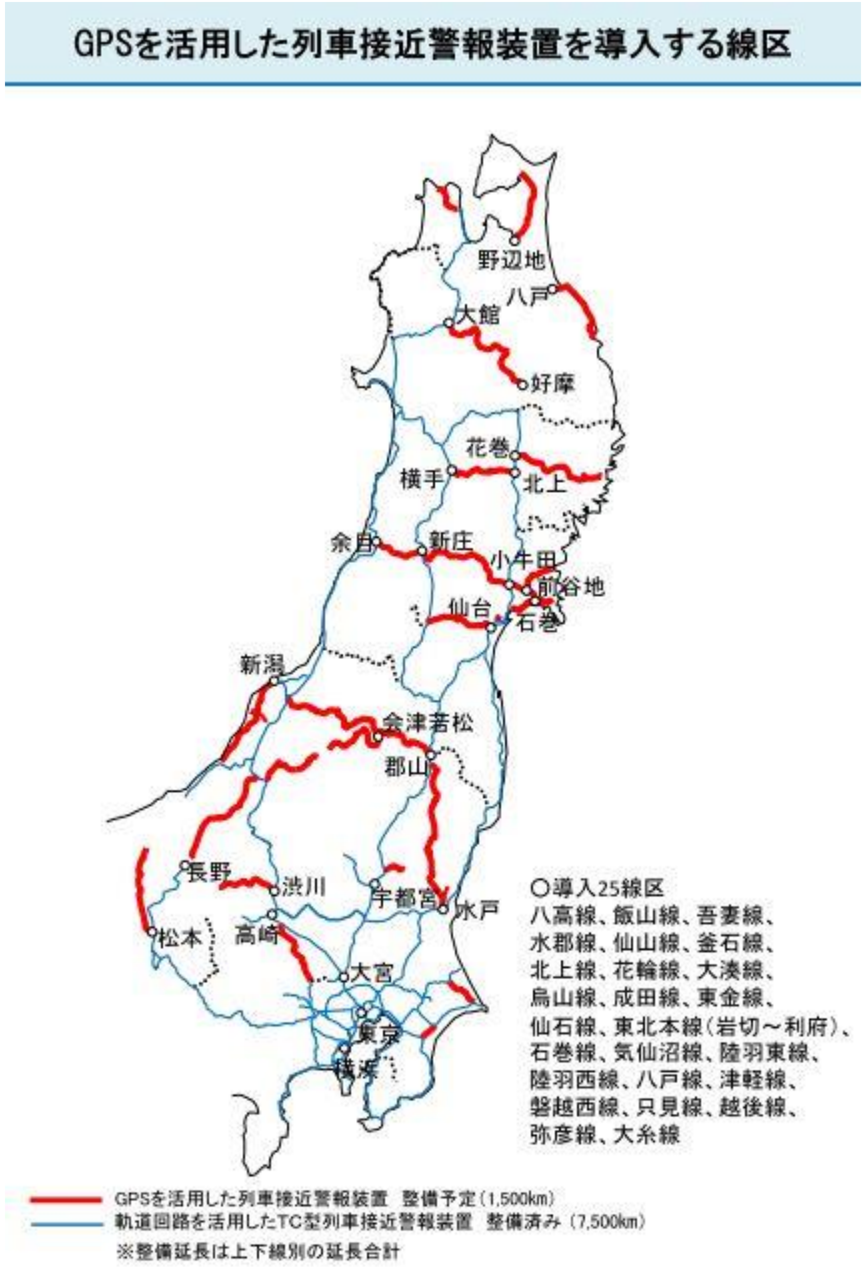
④作業員用端末
・列車位置と作業員の位置の離隔を算出し、所定の距離で警報鳴動

○作業員用端末画面（接近警報時イメージ）

♪下り、接近！
下り、接近！

列番：101D		列番：102D	
在線区間：A駅－B駅		在線区間：D駅－E駅	
遅れ時分：2分		遅れ時分：0分	
60km/h	1350m	70km/h	9560m

1,500m以内に接近⇒接近警報（赤色）
3,000m以内に接近⇒接近注意報（黄色）


GPSを活用した列車接近警報装置を導入する線区

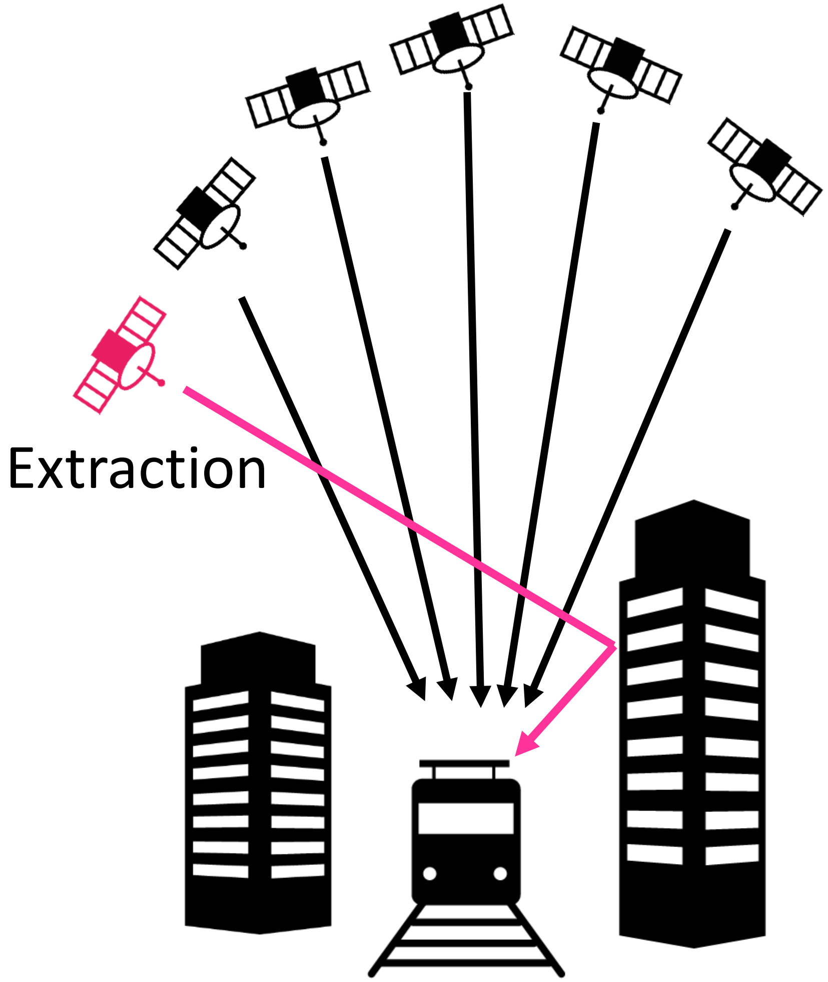
○導入25線区
八高線、飯山線、吾妻線、
水郡線、仙山線、釜石線、
北上線、花輪線、大湊線、
烏山線、成田線、東金線、
仙石線、東北本線（岩切～利府）、
石巻線、気仙沼線、陸羽東線、
陸羽西線、八戸線、津軽線、
磐越西線、只見線、越後線、
弥彦線、大糸線

GPSを活用した列車接近警報装置　整備予定（1,500km）
軌道回路を活用したTC型列車接近警報装置　整備済み（7,500km）
※整備延長は上下線別の延長合計

Objective

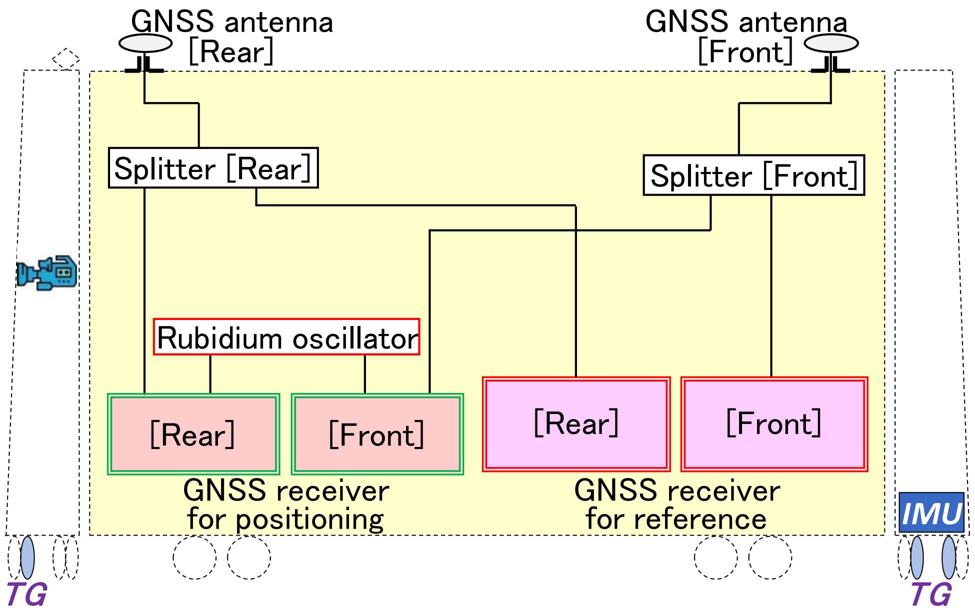
- Analyzing the pseudo-range errors of every satellite using big data obtained in real railway environments.

- Horizontal DGNSS errors are also analyzed.
- Error mitigation technique are also introduced.



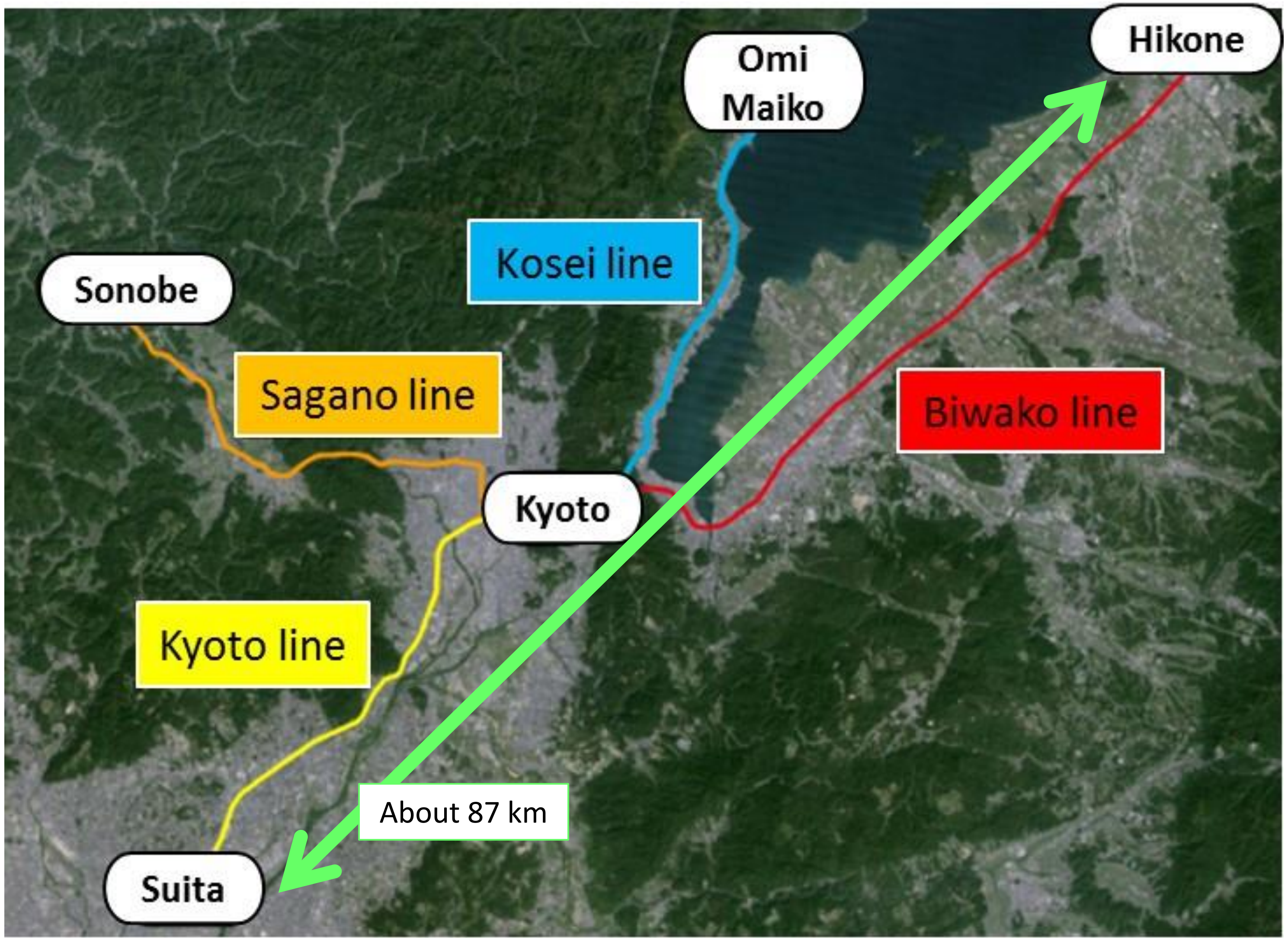
Data Acquisition 1

Test Train for Conventional Line (U@tech)



Interval	0.1 s
Receiver 1	JAVAD Delta-G3T
Receiver 2	NovAtel OEM628
Antenna	NovAtel GPS-703-GGG
Antenna interval	18.21 m
Rubidium oscillator	Stanford Research Systems FS725
Reference station	Receiver : JAVAD Delta-G3T Antenna : JAVAD GrANT-G3

Data Acquisition 2



Google map

Railway lines for test (West Japan Railway Area)

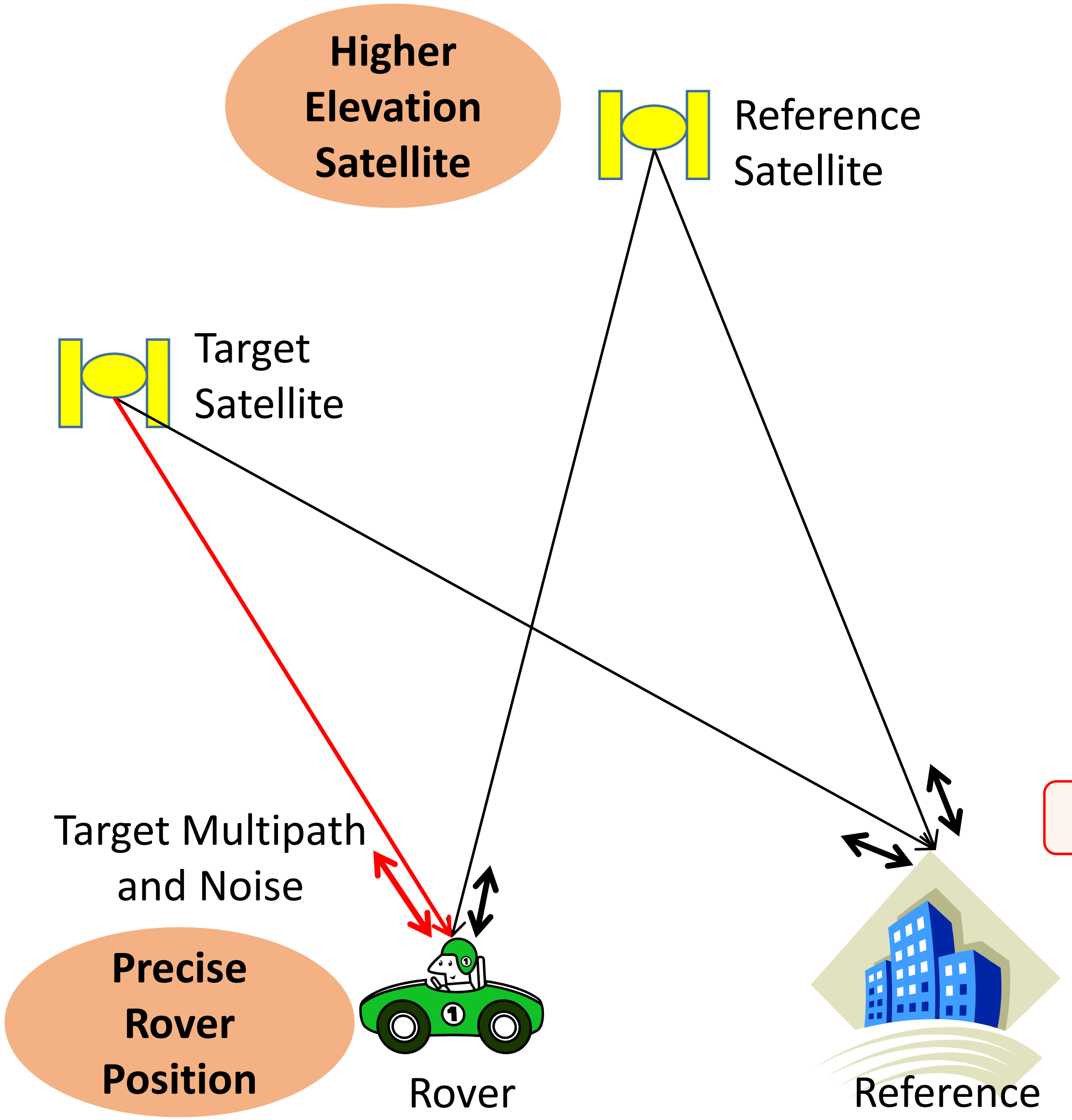
The observational data was collected in sections totaling 171 km on four operating lines extended in four directions from JR Kyoto Station.

Urban areas including spots like the valley of the buildings, plain areas of the suburbs, mountainous areas, etc. The tunnel also exists in part.

The observation was carried out from December, 2012 to February, 2013 (a total of 7 days) and the mileage amounted to a total of 2,000 km.

The important reference positions used in this test were produced using both the antenna trajectory (GIS) and post-processed RTK.

Pseudo-range Errors Analysis



$$\boxed{P_{rov\_ref}^{sv1\_sv2}} = (P_{rov}^{sv1} - P_{ref}^{sv1}) - (P_{rov}^{sv2} - P_{ref}^{sv2})$$

$$= \rho_{rov}^{sv1} + c(dt_{sv1} - dT_{rov}) + ion_{rov}^{sv1} + tropo_{rov}^{sv1} + mp_{rov}^{sv1} + noise_{rov}^{sv1}$$

$$- \left[\rho_{ref}^{sv1} + c(dt_{sv1} - dT_{ref}) + ion_{ref}^{sv1} + tropo_{ref}^{sv1} + mp_{ref}^{sv1} + noise_{ref}^{sv1}\right]$$

$$- \left[\rho_{rov}^{sv2} + c(dt_{sv2} - dT_{rov}) + ion_{rov}^{sv2} + tropo_{rov}^{sv2} + mp_{rov}^{sv2} + noise_{rov}^{sv2}\right]$$

$$+ \left[\rho_{ref}^{sv2} + c(dt_{sv2} - dT_{ref}) + ion_{ref}^{sv2} + tropo_{ref}^{sv2} + mp_{ref}^{sv2} + noise_{ref}^{sv2}\right]$$

$$= \boxed{\rho_{rov}^{sv1} - \rho_{ref}^{sv1} + \rho_{rov}^{sv2} - \rho_{ref}^{sv2}}$$

$$+ \boxed{(mp_{rov}^{sv1} + noise_{rov}^{sv1})} - \boxed{(mp_{ref}^{sv1} + noise_{ref}^{sv1})}_{\text{①}}$$

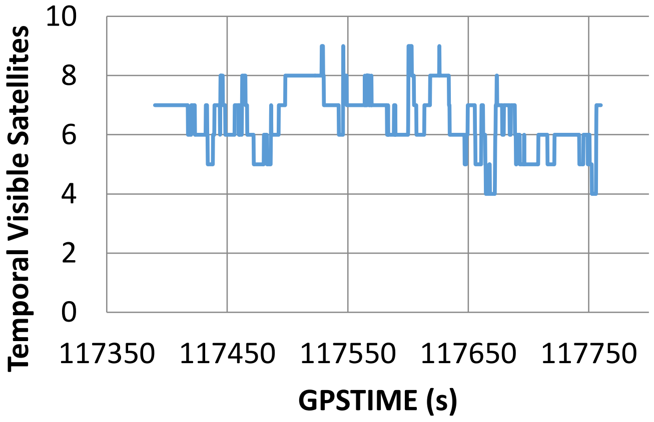
$$- \boxed{(mp_{rov}^{sv2} + noise_{rov}^{sv2})}_{\text{②}} + \boxed{(mp_{ref}^{sv2} + noise_{ref}^{sv2})}_{\text{③}}$$

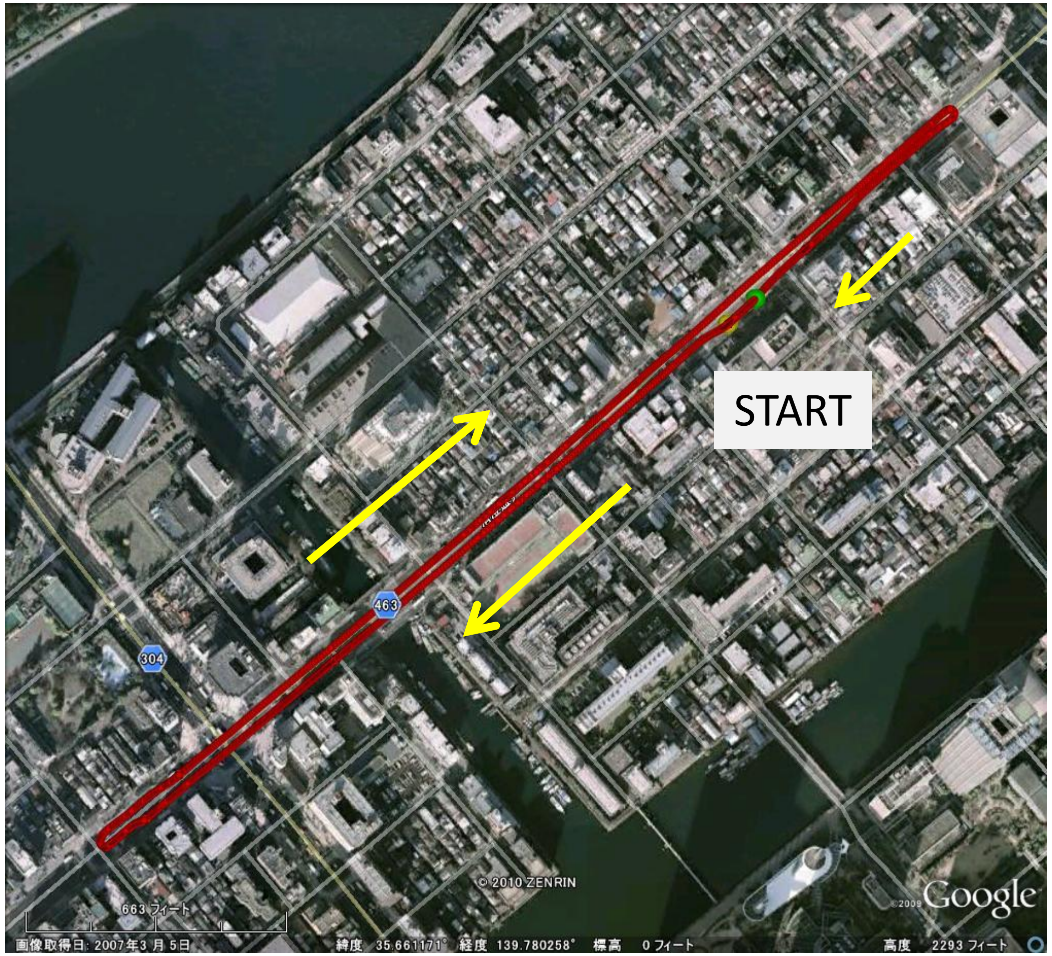
$$\boxed{\text{Target}} = \underset{\text{Raw Data}}{\boxed{\quad}} - \underset{\text{Measure-ments}}{\boxed{\quad}} + \underbrace{\boxed{\text{①}} + \boxed{\text{②}} - \boxed{\text{③}}}_{\text{CC-Difference}}$$

sv1 : Target SV   sv2 : Reference SV (Max Elevation)

Validation of the Proposed Method

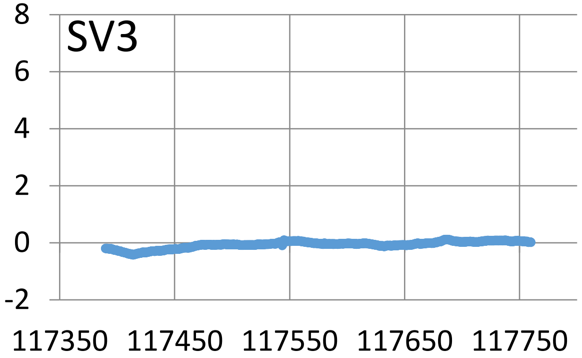
- Test using car in the medium urban areas (Tokyo)
- 6 min 30 sec (5 Hz)
- Geodetic receiver and antenna
- Target satellite was GPS
- Reference SV: PRN-19 (66 degree)
- 9 satellites in view over 10 degree elevation
- Precise car positions were computed by post-processing RTK.

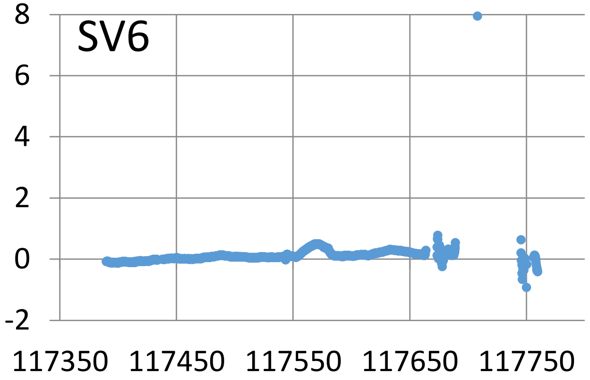


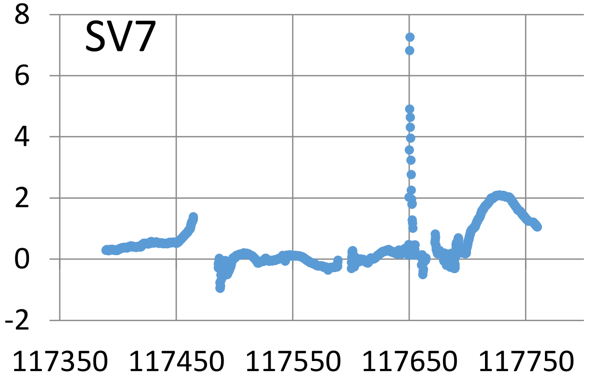


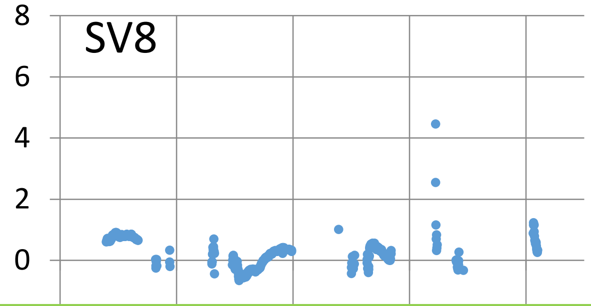
Test route

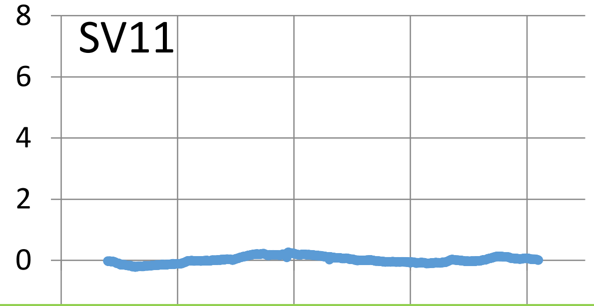
Temporal Pseudo-range Errors of Each Satellite using the Proposed Method

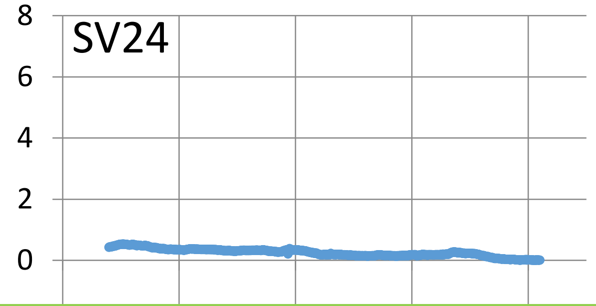




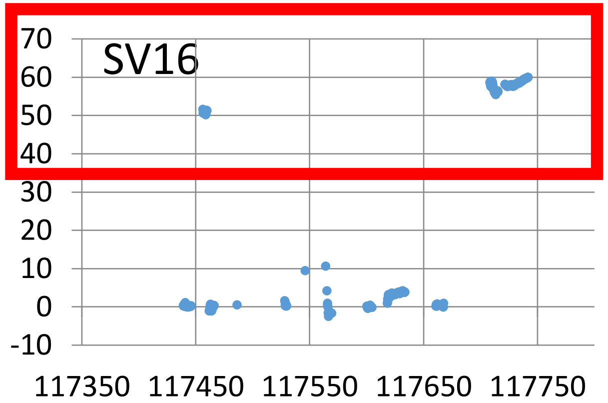


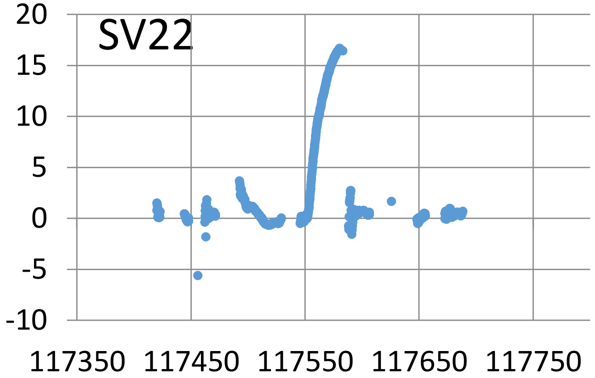




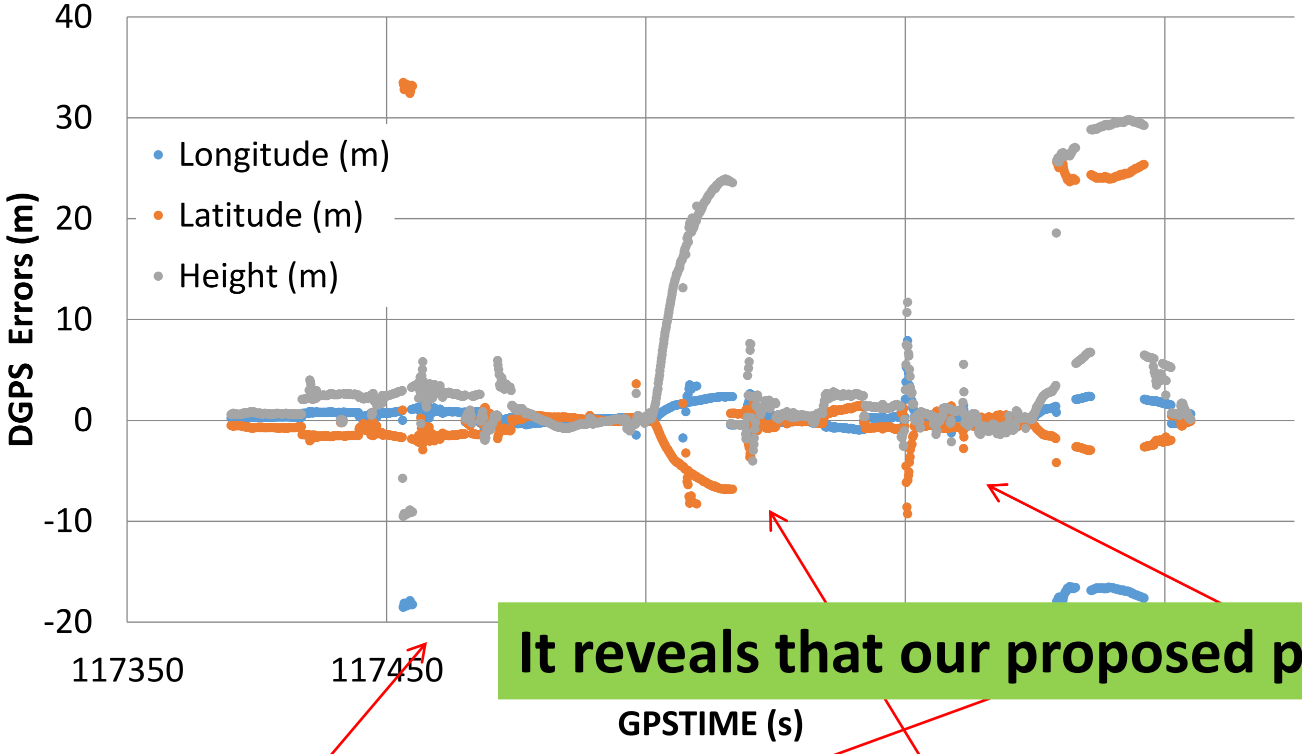


SV16 has over 50 m pseudo-range errors clearly due to Non-Line-Of-Sight signal

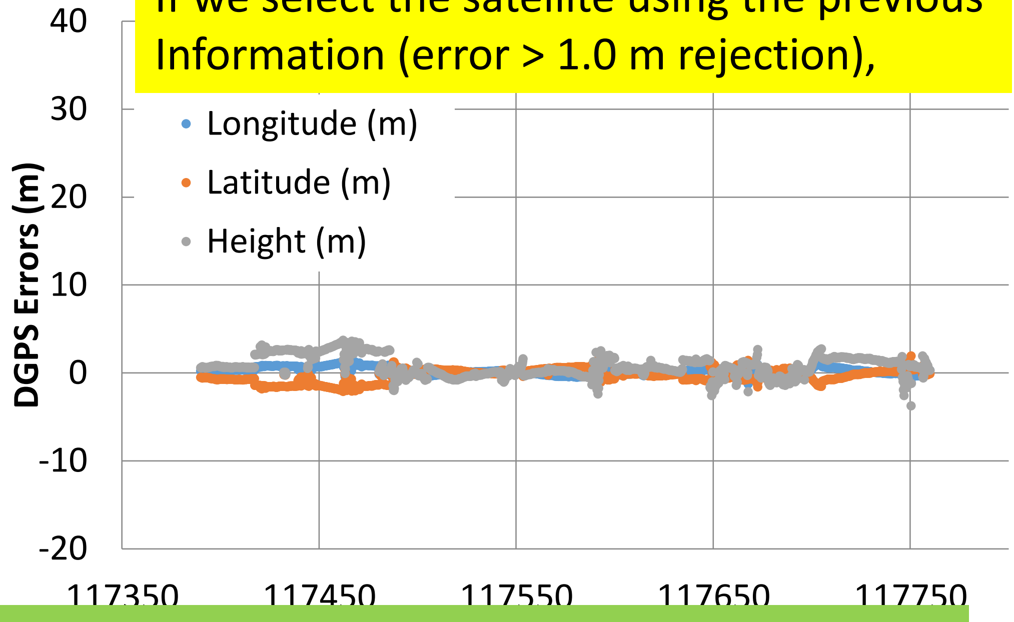




Comparison between DGPS errors and Pseudo-range errors

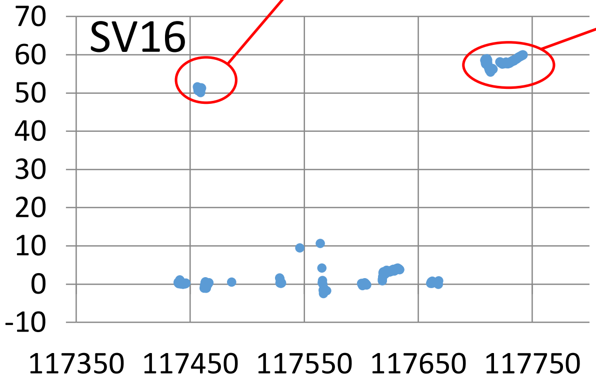


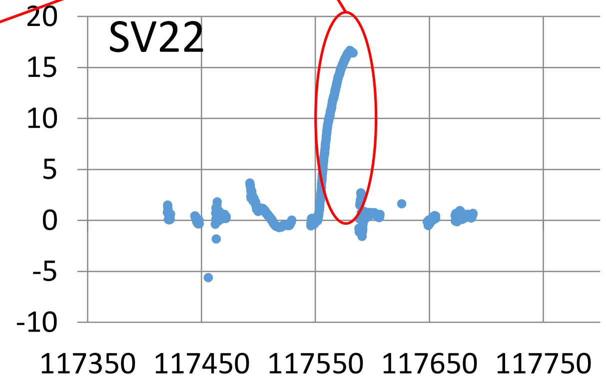
If we select the satellite using the previous Information (error > 1.0 m rejection),

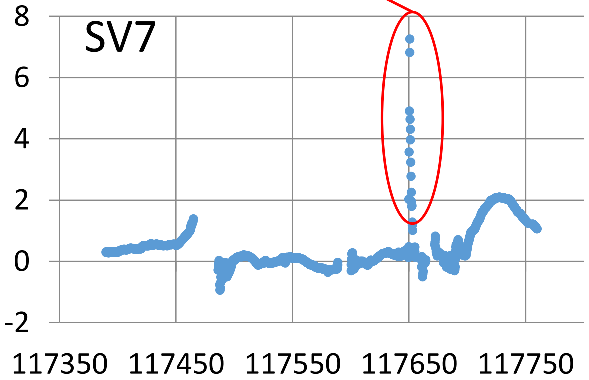


It reveals that our proposed pseudo-range errors generation is correct.

	Average NVS	Horizontal (1σ)	Vertical (1σ)
Normal	**6.49**	**9.07 m**	**8.54 m**
+MP rejection	**6.08**	**0.81 m**	**1.13 m**







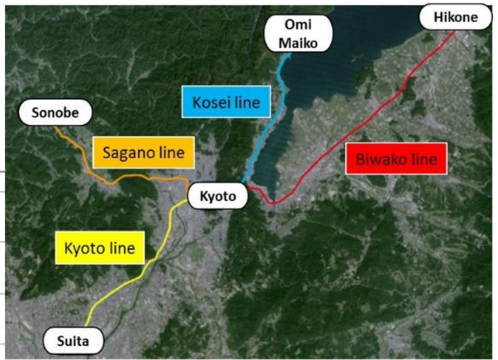
Error Analysis obtained in Real Railroad Environment

Analysis condition

Satellite	**GPS and QZSS**
Minimum C/N0	**25 dB-Hz**
Mask angle	**10 degree**
Reference satellite	**Maximum elevation and $C/N_0 > 43.0$ dB-Hz**
GDOP	**< 30**
Interval	**1.0 sec**
Smoothing	**Not applied (default 2 sec in JAVAD receiver)**

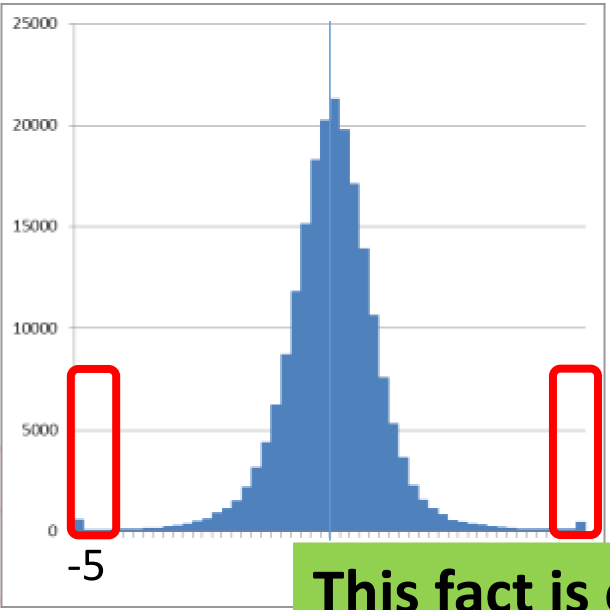
Pseudo-range errors were analyzed using the previous method.
The data while the train stopped at the station was not included.
DGNSS (GPS/QZS) was also evaluated.

Statistical Results of all Pseudo-range Errors



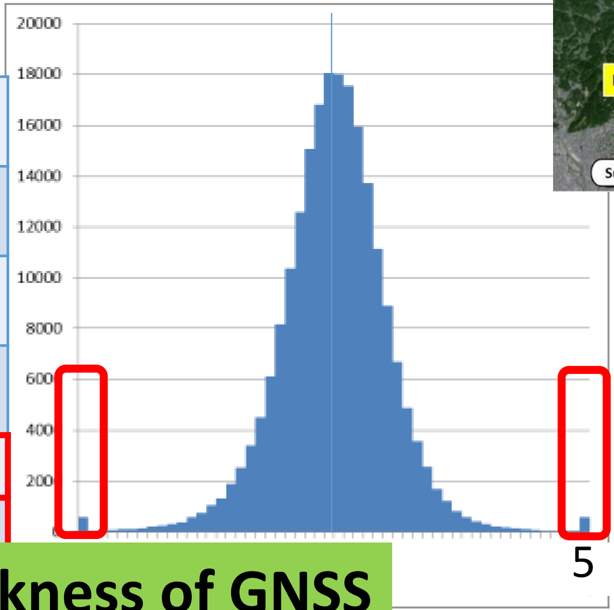
Sagano

Total	**34138 s**
1σ	**1.17 m**
Average	**0.04 m**
Maximum	**40.1 m**
99.9 %	**8.8 m**
99.99 %	**19.4 m**



Kosei

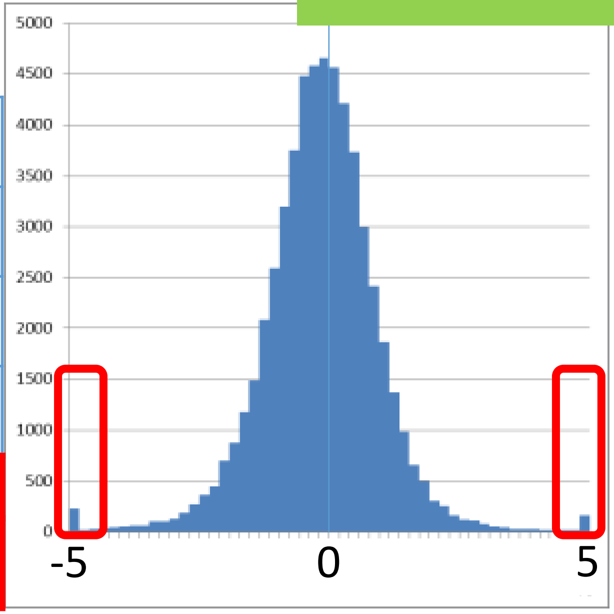
Total	**43064 s**
1σ	**1.43 m**
Average	**0.01 m**
Maximum	**53.3 m**
99.9 %	**15.4 m**
99.99 %	**32.3 m**



This fact is exactly the weakness of GNSS

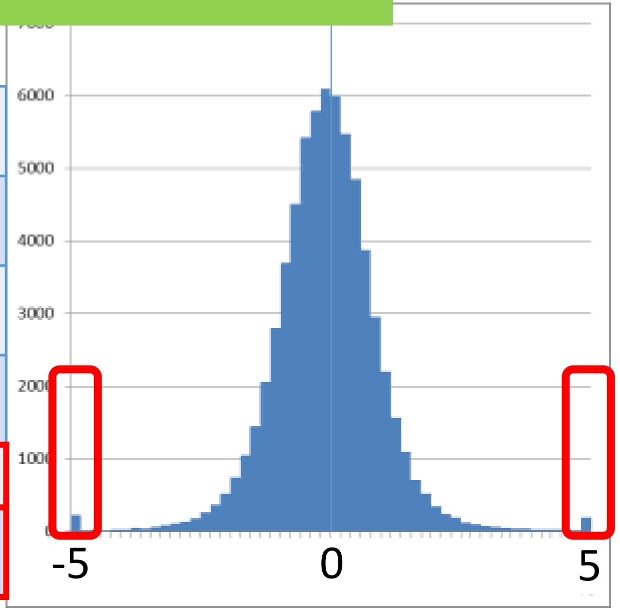
Kyoto

Total	**9318 s**
1σ	**1.32 m**
Average	**-0.17 m**
Maximum	**49.9 m**
99.9 %	**10.3 m**
99.99 %	**19.8 m**



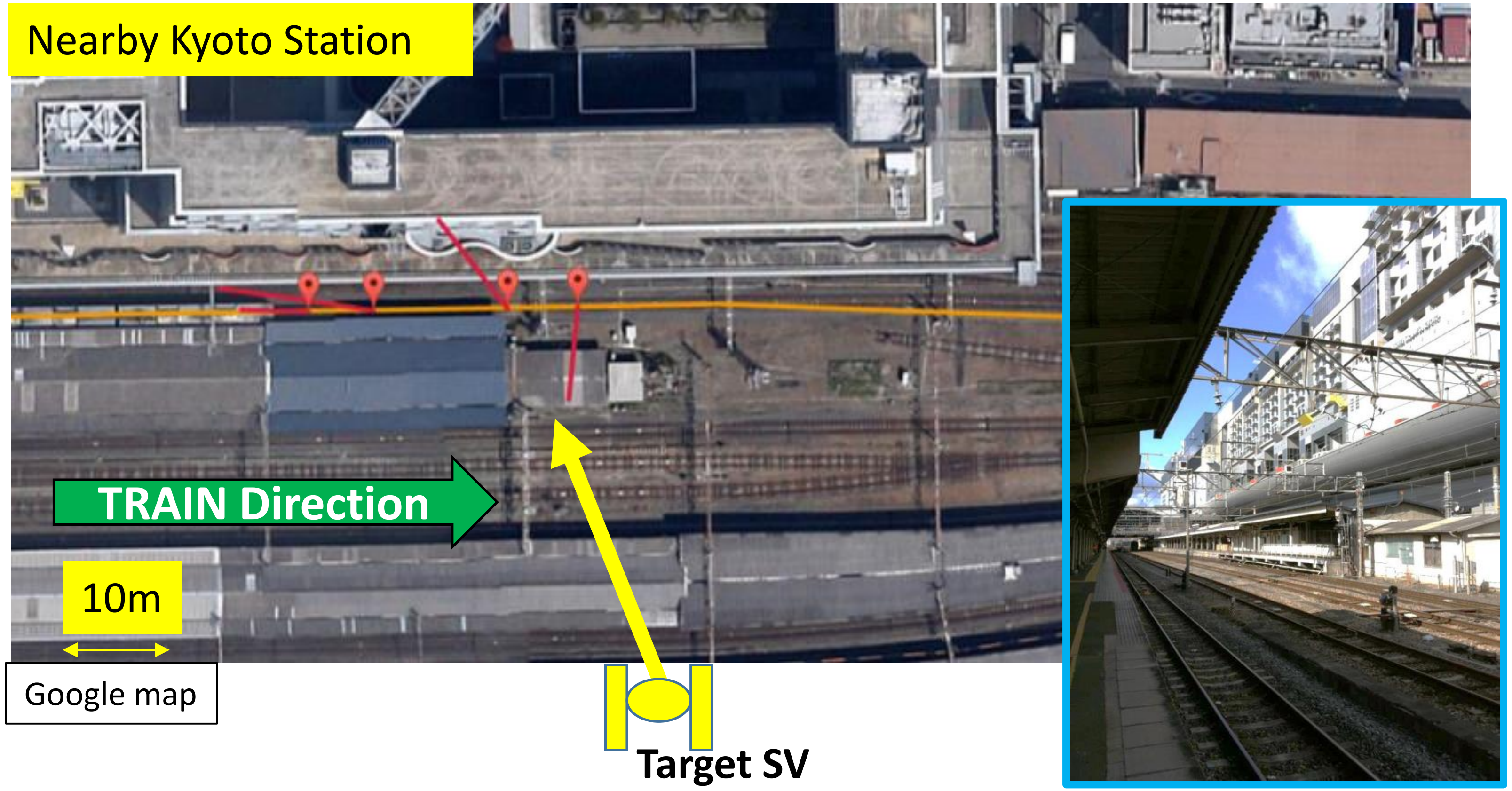
Biwako

Total	**10735 s**
1σ	**1.317 m**
Average	**-0.08 m**
Maximum	**43.3 m**
99.9 %	**9.3 m**
99.99 %	**16.1 m**



One Shot of Large Errors nearby Kyoto Station

Heavily deteriorated satellite（Ele=41, Azi=162）				
Places (from left)	①	②	③	④
Pseudo-range Error[m]	7.6	18.9	15.3	-7.9
Actual Error [m]	8.3	19.4	14.0	11.5

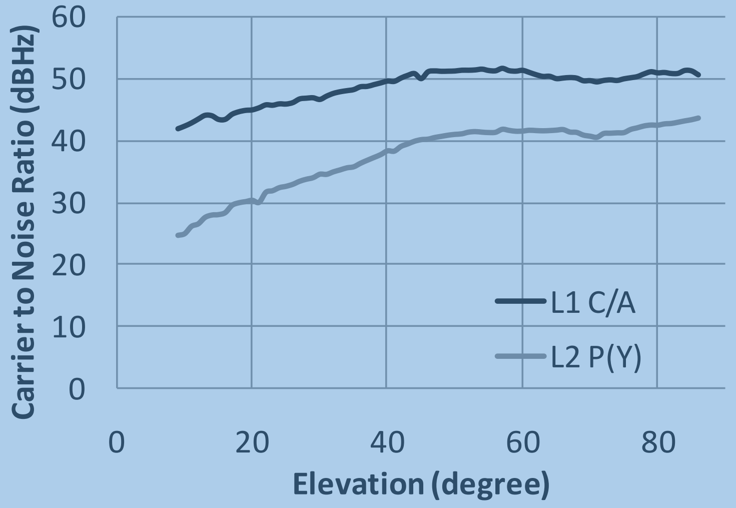


According to the investigation of all test results. The pseudo-range errors over 10 m occurred at the following places.

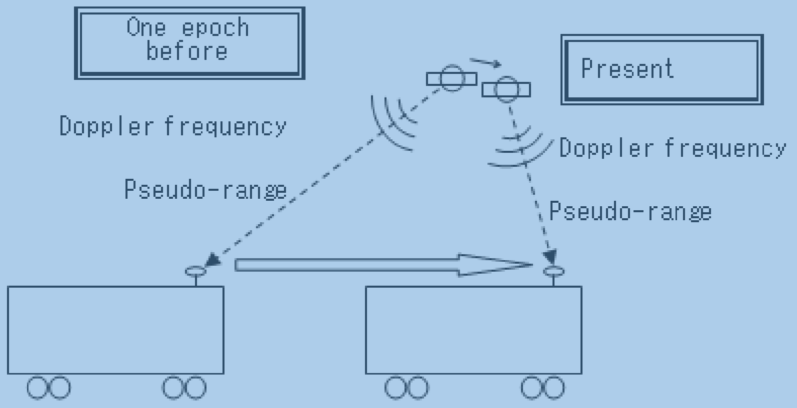
1) **Nearby station**
2) **Under or nearby overpass**
3) **Close to hill or mountain**
4) **Both ends at tunnel**

Proposed Pseudo-range Error Mitigation

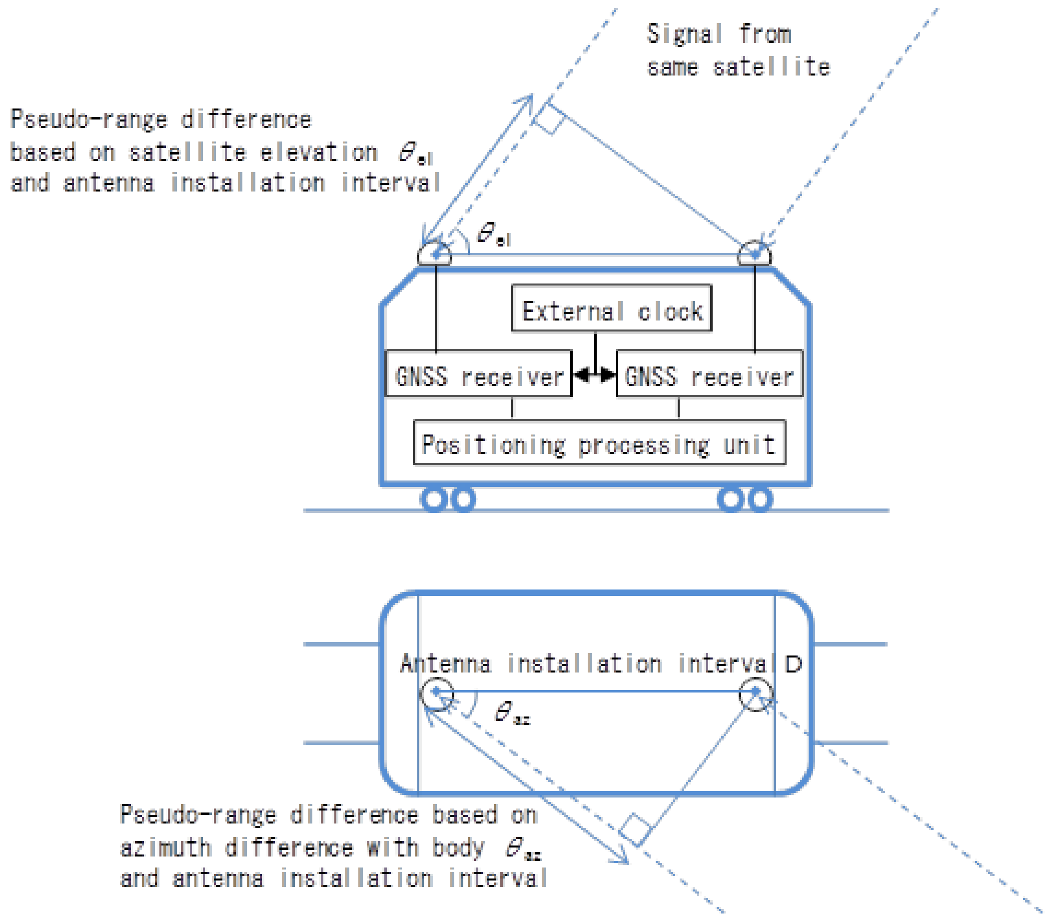
1. Elevation dependent C/N_0 threshold



2. Doppler frequency based satellite selection



3. Use of the antenna installation intervals



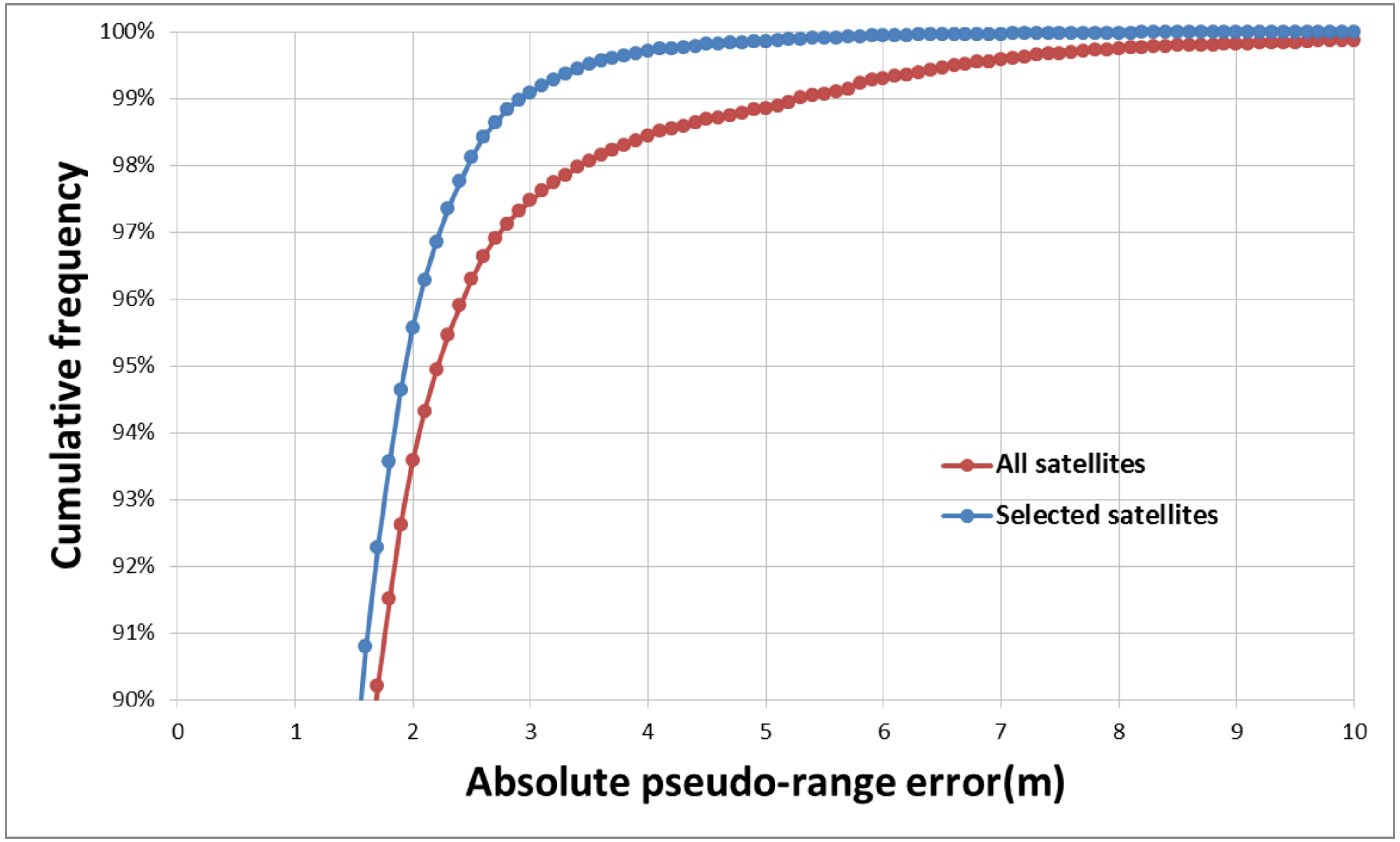
Ideal pseudo-range difference $= D \cdot \cos\theta_{el} \cdot \cos\theta_{az}$

Evaluation of the Multipath Mitigation Technique

- We compared the **pseudo-range errors** between the use of **all available satellites** and the use of **selected satellites** using the proposed three techniques.
- Data : “Kyoto” and “Biwako” line (3.5 hours, 12/11/2012)
- Based on our many experimental data, the thresholds were set. The following table summarizes statistical results comparing the two cases.

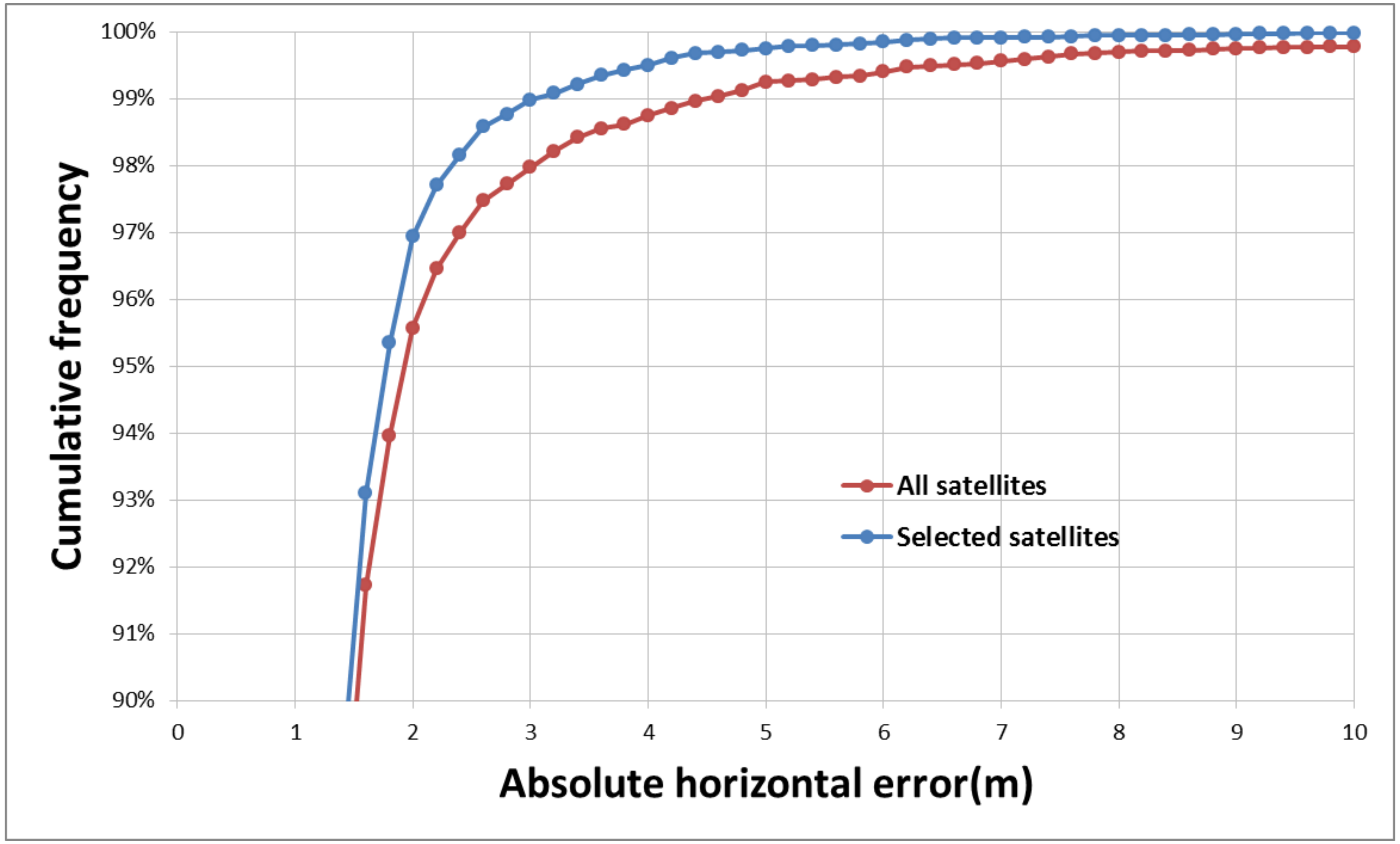
	All satellites used	**Selected satellites used**
Number of samples	97407	73779
1σ	1.32 m	0.99 m
Average	–0.17 m	–0.16 m
Maximum	38.7 m	25.3 m
Number of samples with error over 5 m	730	108

Cumulative Frequency of pseudo-range Errors



Percentage Point	All satellites used	Selected satellites used
99.00%	5.3 m	3.0 m
99.90%	11.1 m	5.5 m

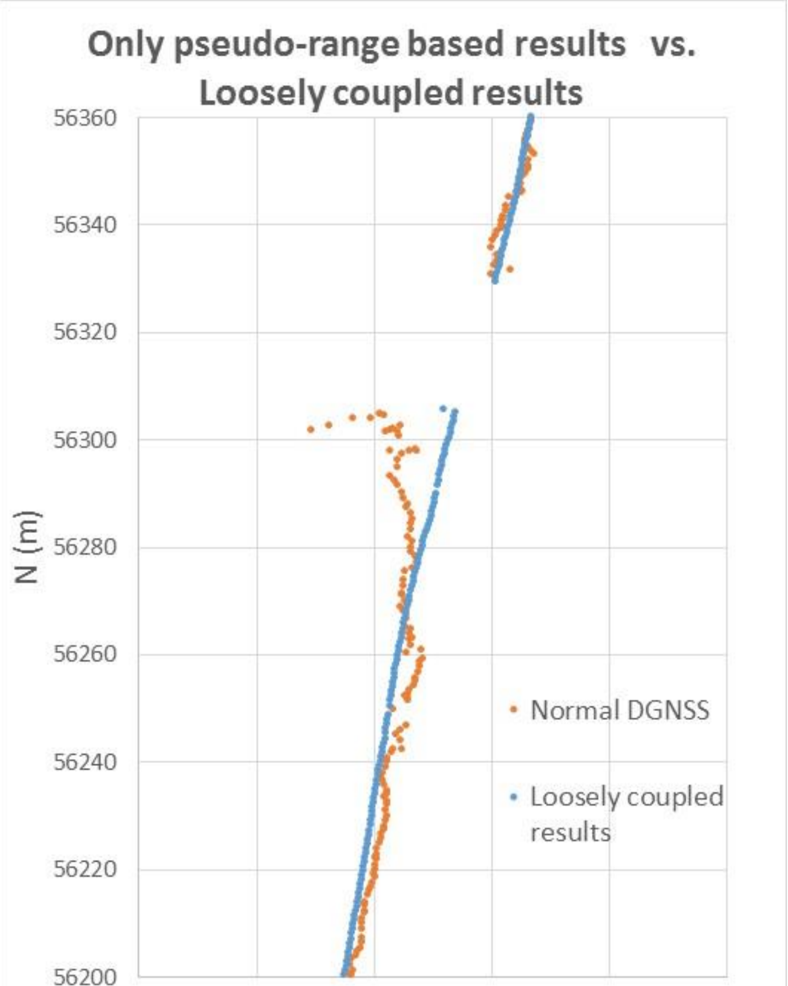
Cumulative Frequency of Horizontal Errors



Percentage Point	All satellites used	Selected satellites used
99.00%	4.6 m	3.1 m
99.90%	16.0 m	6.5 m
Positioning rate	90.3 %	88.0 %

Loosely Coupled KF using Velocity Information

- Doppler frequency derived **“velocity”** is quite tolerant to strong multipath condition.
- Pseudo-range based **“position”** is not tolerant to strong multipath condition.
- We need to put them together efficiently.
- Data : “Kyoto” and “Biwako” line (3.5 hours, ***10Hz***, 12/11/2012)



One shot of comparison…

$$x_{k+1} = Fx_k + Gw_k$$

$$y_k = Hx_k + v_k$$

$$\boldsymbol{x_k} = [x(k), y(k), v_x(k), v_y(k), a_x(k), a_y(k)]^{\mathrm{T}}$$

$$x(k+1) = x(k) + v_x(k)\Delta T + a_x(k)\Delta T^2 / 2.0$$

$$y(k+1) = y(k) + v_y(k)\Delta T + a_y(k)\Delta T^2 / 2.0$$

$$v_x(k+1) = v_x(k) + a_x(k)\Delta T$$

$$v_y(k+1) = v_y(k) + a_y(k)\Delta T$$

$$\boldsymbol{F} = \begin{bmatrix} 1 & 0 & \Delta T & 0 & \Delta T^2/2 & 0 \\ 0 & 1 & 0 & \Delta T & 0 & \Delta T^2/2 \\ 0 & 0 & 1 & 0 & \Delta T & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{y_k} = [x(k), y(k), v_x(k), v_y(k)]^{\mathrm{T}}$$

$$\boldsymbol{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

x_k : *state vector*

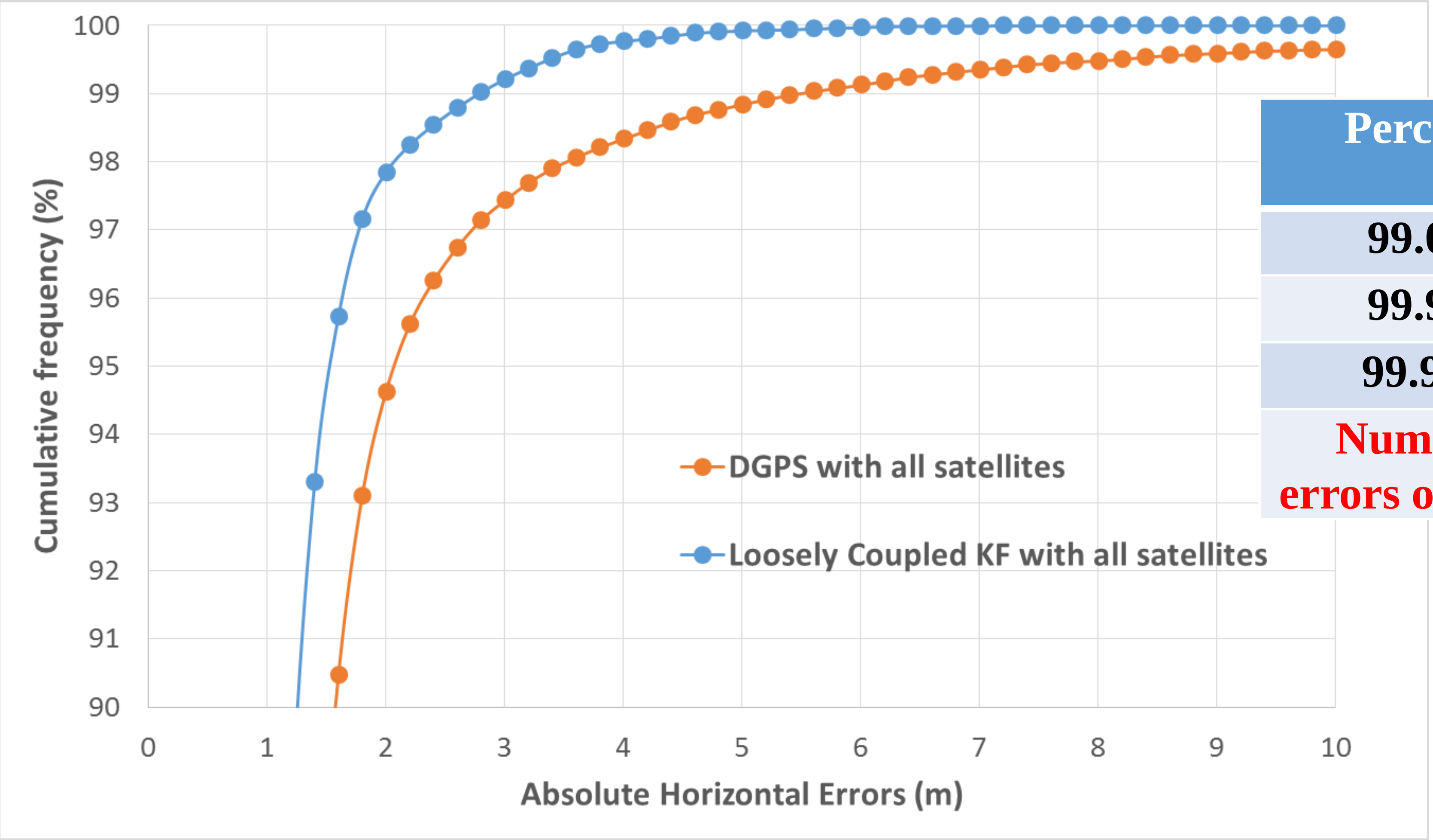
w_k : *system noise*

F : *state transition matrix*

G : *noise distribution matrix*

Velocity information indeed enables us to provide smooth and small jump results

Cumulative Frequency of Horizontal Errors



Percentile	DGNSS	Loosely Coupled KF
99.00%	5.4 m	2.8 m
99.90%	19.2 m	4.6 m
99.99 %	60.8 m	6.6 m
Number of errors over 10 m	369	2

Conclusions

- Performance evaluation of GNSS based railway navigation was conducted using the quite valuable raw data obtained in the real railway environments.
- The results were as we expected. The most of errors were like beautiful normal distribution except for the large jumps over 10 m.
- Large jumps occurs frequently at Nearby station, Nearby overpass, Close to hill or mountain and Both ends at tunnel.

- Good quality satellite selection method was proposed. Approximately, 65 % of large errors were reduced.
- Loosely coupled with velocity information was also evaluated. At the 99.99 % percentile results, the error was reduced dramatically from 60.8 m to 6.6m.
- Fundamental results for integrity monitoring was prepared.

Acknowledgment

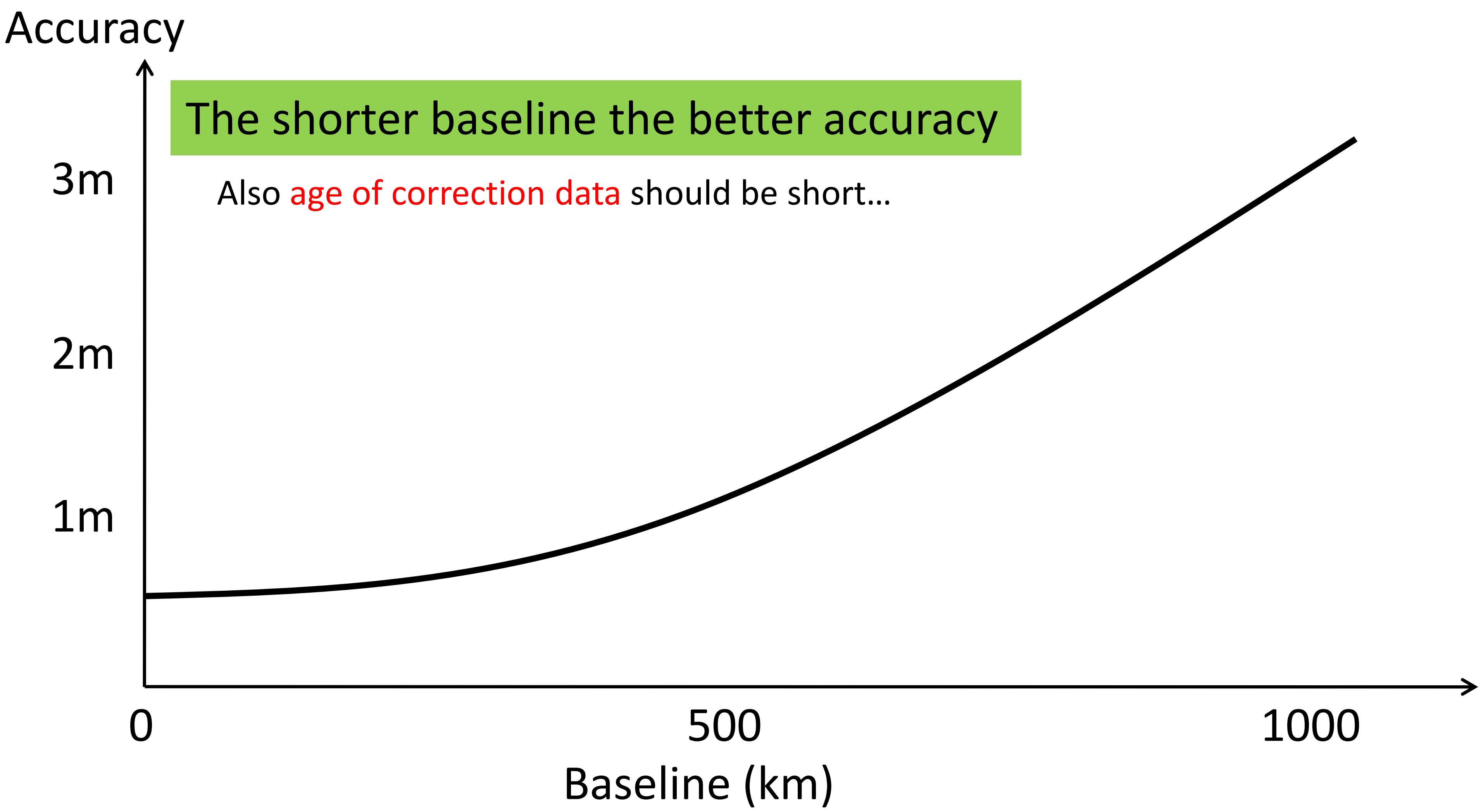
- The authors express their sincere gratitude to everyone concerned at the Japan Aerospace Exploration Agency, which offered equipment, and at the West Japan Railway Company, JR West Japan Consultants Company, Geospatial Information Authority of Japan, and JENOBA Co., Ltd., which cooperated in the data acquisition.

appendix

DGPS mitigates …

Source	Potential error size	Error mitigation using DGPS
Satellite clock model	2 m (rms)	0.0 m
Satellite ephemeris prediction	2 m (rms) along the LOS	0.1 m (rms)
Ionospheric delay	2-10 m (zenith) Obliquity factor 3 at 5°	0.2 m (rms)
Tropospheric delay	2.3-2.5m (zenith) Obliquity factor 10 at 5°	0.2 m (rms) + altitude effect
Multipath (open sky)	Code : 0.5-1 m Carrier : 0.5-1 cm	→
Receiver Noise	Code : 0.25-0.5 m (rms) Carrier : 1-2 mm (rms)	→

Limitations of DGPS



The shorter baseline the better accuracy

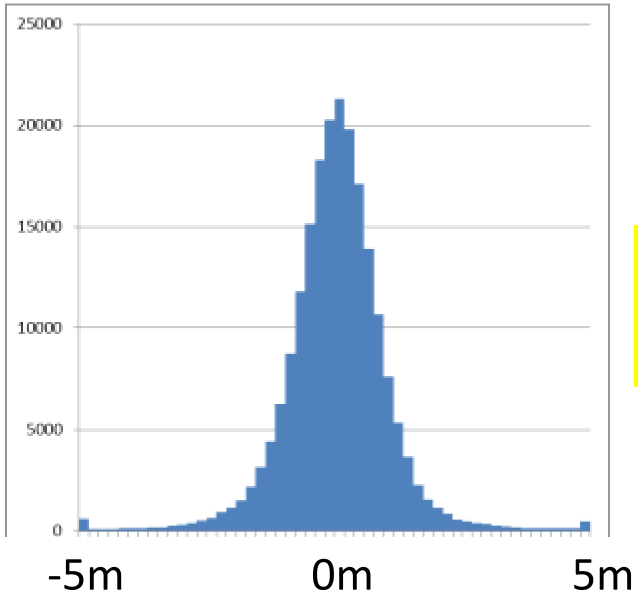
Also age of correction data should be short…

Relationship between DGNSS and Pseudo-range Errors

- In the case of DGNSS within 100 km baseline, the dominant part of errors will be “**multipath and DOP**” (GDOP<30). Satellite position, clock and atmospheric errors are negligible in terms of desi-meter accuracy.

Horizontal DGNSS Errors

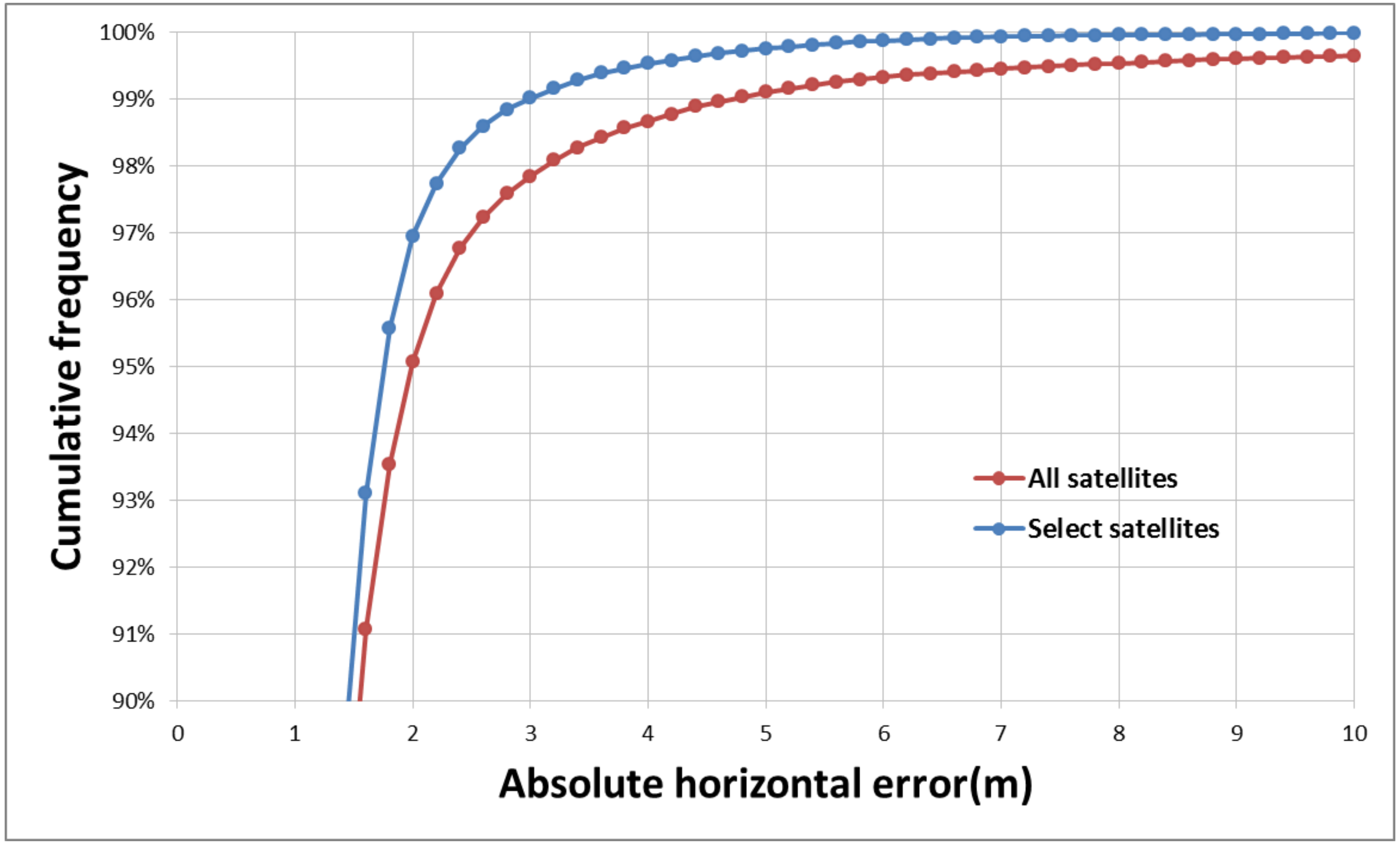
=



Error distribution

× HDOP

Cumulative Frequency of Horizontal Errors(Interval:10Hz)



Percentage Point	All satellites used	Selected satellites used
99.00%	4.8 m	3.0 m
99.90%	39.8 m	6.5 m